Backcalculation Validation Through Field Instrumentation

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Abstract. The response of instruments embedded in pavements can be used to validate and calibrate empirical-mechanistic design and analysis approaches. This paper compares *actual* pavement responses measured at the Virginia Smart Road with those determined using theoretical models and backcalculated layer moduli. Falling Weight Deflectometer (FWD) tests were conducted as each layer was built, and bimonthly after the pavement was complete. The moduli of each layer were backcalculated using several approaches. The response of the instruments to the FWD loading was recorded together with the moisture content of the granular layers and the temperature of the hot-mix-asphalt (HMA) layers. Seasonal and long-term changes in structural capacity were monitored periodically to accurately assess any changes in the material properties. A detailed backcalculation procedure was defined, which included provisions to combine thin pavement layers and criteria to determine the reasonableness of the determined moduli. The procedure also considered changes in the HMA layers due to temperature fluctuations, temporal changes in the layer moduli due to strengthening of the cement treated layer, and stress-dependency of the granular layers. The backcalculated moduli were validated by conducting FWD tests directly on top of pressure cells and strain gages and comparing the measured responses with theoretical stresses and strains at the instrument locations determined using linear-elastic and nonlinear-elastic models. In general, the results show that the calculated stresses are comparable to the measured stresses. However, non-linearity may need to be considered when computing stresses in the granular layers. The strains computed in the HMA layers were also consistent between measured and computed values. Pavement instrumentation proved to be useful for the validation of theoretical material models against *actual* pavement performance. This practice is expected to become particularly important and possibly gain widespread acceptance as we move to full implementation of empirical-mechanistic pavement design and analysis methodologies.

INTRODUCTION

Full and defensible implementation of mechanistic pavement design methodologies requires the validation of “theoretical” material models versus true field performance. A number of “mechanistic” or empirical-mechanistic flexible pavement design methodologies have been developed. These usually rely on fundamental models of vehicular loading, material properties, and structural system response to loading and environmental interaction. The computed pavement responses are used to predict roughness, rutting, and cracking using empirically determined transfer functions.

The mechanistic analysis approaches require knowledge of the mechanical properties of all pavement materials. Nondestructive testing, i.e., the Falling Weight Deflectometer (FWD), is commonly used to quantify the response of a pavement structure to known loads. The measured deflection basins are used to estimate in situ elastic moduli for each pavement layer using a backcalculation approach. The backcalculation procedure involves calculation of theoretical deflections under the applied load using assumed pavement layer moduli. These theoretical deflections are compared to measured deflections and the assumed moduli are then adjusted in an iterative procedure until the theoretical and measured deflection basins reach an acceptable match. The backcalculated moduli can be used to calculate stresses and strains in the pavement structure that may be used in distress models to evaluate damage accumulation under traffic and to predict pavement failure. The backcalculated moduli may also be used to evaluate corrective measures such as overlay thickness. Unfortunately, analysis of data from some testing facilities, such as WesTrack, repeatedly demonstrated that a solution based solely on the best possible match between the theoretical and measured deflection basins does not necessarily produce accurate or meaningful results (*1*).

In recent years, pavement instrumentation has been increasingly used to validate and calibrate mechanistic design and analysis approaches, such as those used for backcalculation of *in situ* pavement material moduli. Pavement instrumentation allows for monitoring pavement material performance and quantitatively measuring pavement system response to loading and environment. Ullidtz et al. measured stresses and strains in a homogenous layer and found good agreement between predicted vertical stresses and measured stresses (*2*). However, the authors recommended measurements of stresses and strains for different loading and material combinations. Attempts were made by Scullion et al. to verify backcalculation procedures through instrumentation of pavement sections with multi-depth deflectometers (MDD) (*3*). Some success was achieved utilizing analyses based only on linear elasticity.

The objective of this paper is to compare *actual* pavement responses measured at the Virginia Smart Road to those determined using theoretical models and backcalculated layer moduli in the first 8 sections (A through H) of the 12 testing sections. The last four sections are being studied separately because they include non-traditional reinforcing materials and thus require a different analysis approach.

To achieve this objective, the moduli of each layer were backcalculated as explained in the following section. The response of the instruments to the FWD loading was recorded together with the moisture of the granular layers and the temperature of the hot-mix-asphalt (HMA) layers. A data acquisition software developed at Virginia Tech was used to capture the load response versus time from the pressure cells and strain gages (*4*). Nassar et al. (*5*) reported on the use of five FWD loads to determine the pressure distribution under the BM-25.0 layer at the Virginia Smart Road.

FALLING WEIGHT DEFLECTOMETER TESTING

The pavement research facility at the Virginia Smart Road has 12 heavily instrumented flexible pavement sections (Figure 1). The instruments, including pressure cells, strain gages, thermocouples, moisture sensors, and frost probes, were embedded during the construction of the road.

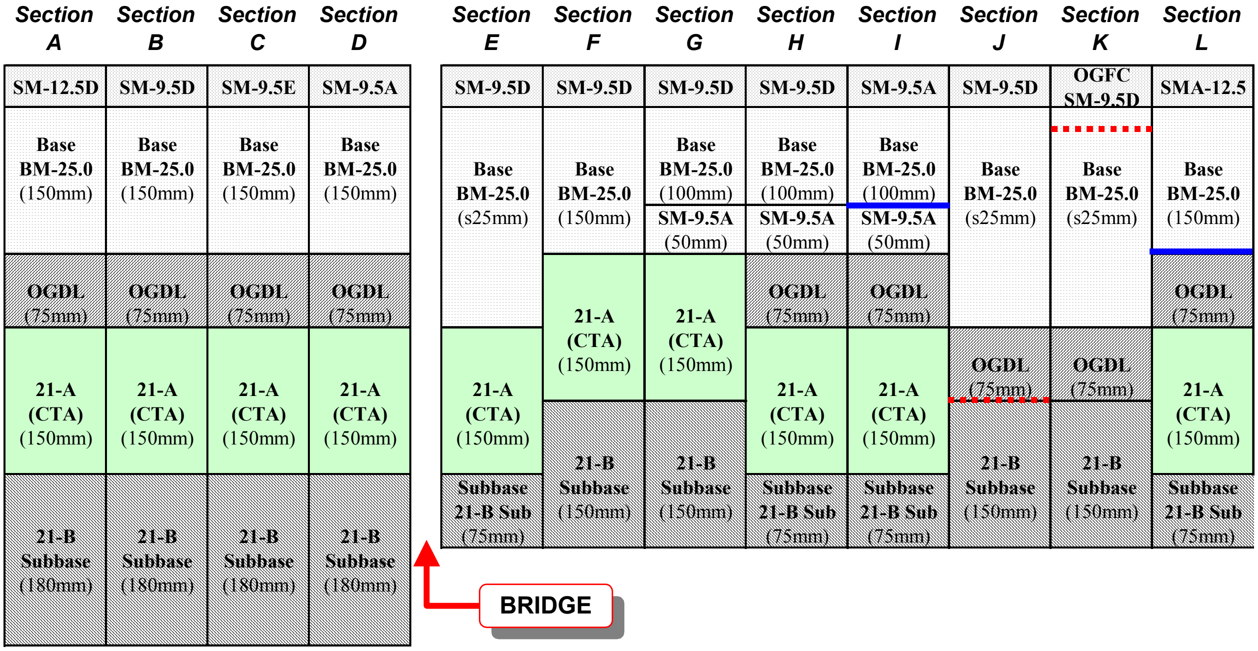

FIGURE 1 Pavement Cross-Sections at the Virginia Smart Road.

A Dynatest model 8000 FWD unit was used to monitor the structural capacity of the different pavement systems. Several FWD testing schemes were conducted:

1. As-Constructed Structural Capacity: FWD testing was conducted after the construction of each layer. The same locations were used for each successive layer. The moisture and temperature of the placed layers were measured at the time of testing. Five load levels were used to determine possible non-linear behavior of the materials. Two plate sizes (300 and 457mm in diameter) were used on the granular materials.
2. Periodical (Seasonal) and In-Service Monitoring: FWD testing was conducted bi-monthly on the selected locations after the completion of construction to investigate the effect of seasonal variation on the layer moduli.
3. Structural Capacity Survey: FWD testing was conducted every 10 m on both instrumented and non-instrumented lanes of each section to assess the within-section variability. Figure 2 show the maximum FWD deflections (at the center of the loading plate) measured on the instrumented lane in April and May 2000.
4. Instrument Responses to FWD Loading: FWD testing was carried out on selected sections on top of pressure cells and strain gages in different occasions. Loads of 31, 40, 49, and 58kN were used.

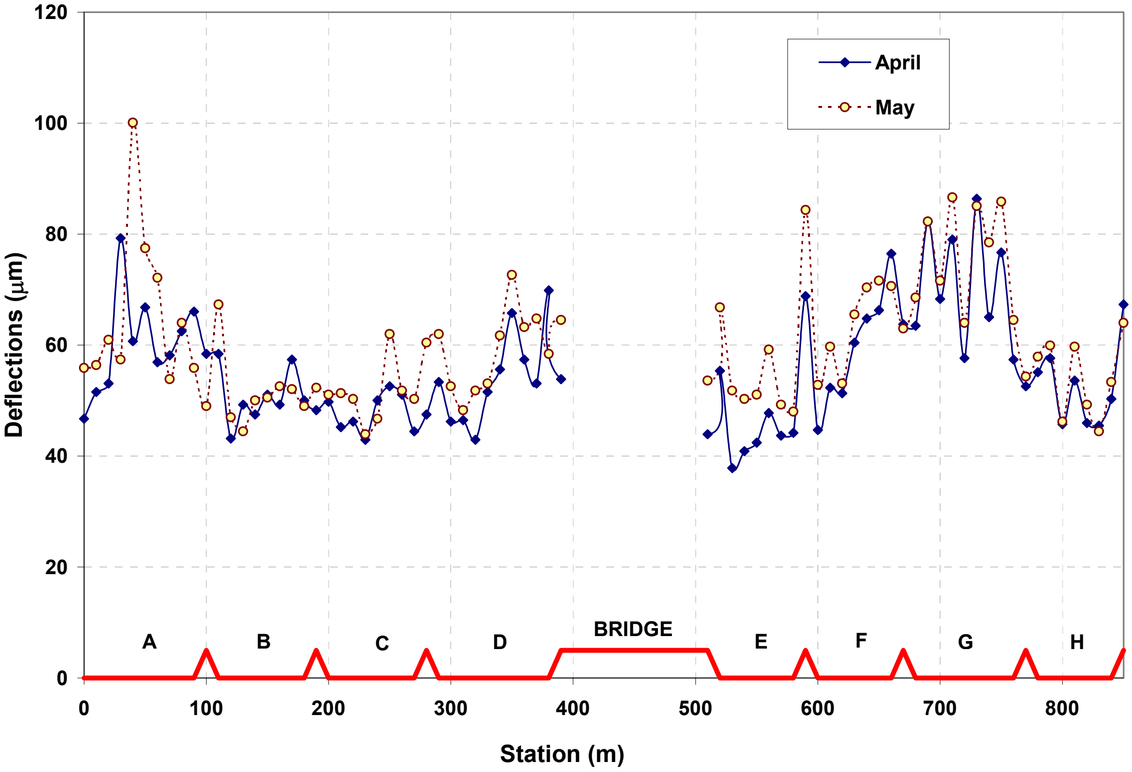

FIGURE 2 Deflections on the Instrumented Lane in April and May 2000.

SEASONAL VARIATIONS

Figure 2 shows the significant differences among the deflections measured for the first four sections as well as between measurements under different environmental conditions for the same section. A temperature correction equation for the maximum deflection (D_0) was established based on the deflections measured at different temperatures on the same locations.

The data for each section was analyzed separately and a multiplicative correction factor was determined using regression analysis. For example, Figure 3 shows the models determined for the first four sections with the corresponding coefficient of determination. Correction factors for transforming deflections measured at different temperatures to a standard 25°C were obtained by normalizing the exponential equations determined for each section. The correction factors determined for all sections are compared in Figure 4. The equation using the average parameters is presented as a solid dark line. Thus, on average the normalized deflection at 25°C can be determined using the following equation:

$$D_0(25) = D_0(T)e^{-0.279(T-25)} \qquad (1)$$

where,
$D_0(T)$ = Center deflection (µm) at Temperature T; and
T = Temperature (°C) at the bottom of the wearing surface (38 mm from the surface).

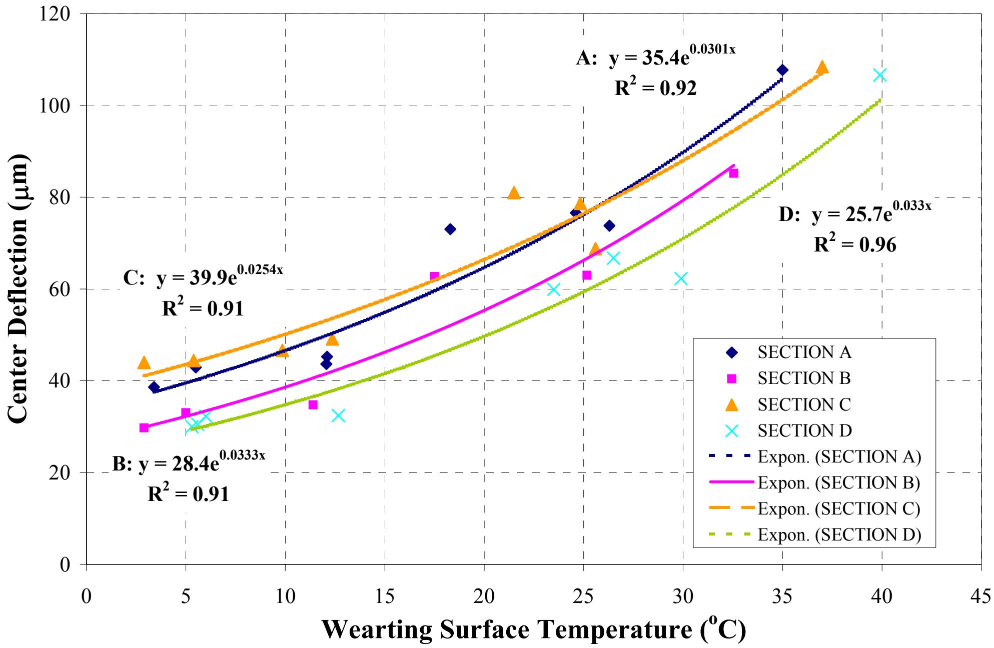

FIGURE 3 Deflections Measured at Different Temperatures, Sections A Though D.

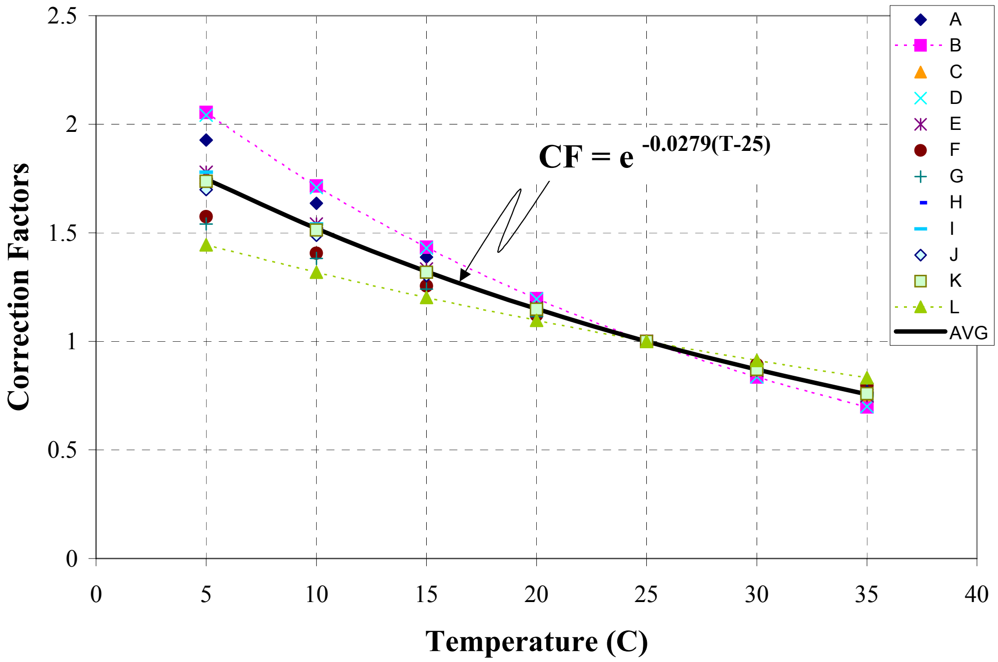

FIGURE 4 Temperature Correction Factor for the Maximum Deflection.

SUBGRADE ANALYSIS

Before conducting the moduli backcalculation for the pavement layers, a comprehensive analysis of the FWD measurements on the subgrade was conducted (*6*). The "as-built" modulus of the subgrade for all the experimental sections was estimated (Table 1) using both a semi-infinite, linear elastic, homogenous half-space (one-layer system), and a two-layer system (modeled with ELSYM5). The results are summarized in Table 1. The average surface modulus without considering the first two sensors was also computed for the effect of the loading plate.

TABLE 1 Subgrade Moduli Using Different Analysis Approaches

Section	Two-Layer (40 kN load)		Two-Layer (40 kN load)	
	Shallow Foundation	Modulus (Mpa)	All Deflections & Loads	D_2-D_6 & All Loads
A	No	345	335	351
B	No	379	395	423
C	No	293	293	306
D	No	276	280	296
E	7.6-15.2m	241	258	273
F	7.6m	207	274	292
G	3.8-5.1m	293	352	398
H	No	207	268	261

MODULI BACKCALCULATION SOFTWARE REVIEW

Currently, there are many backcalculation software packages in use. Most backcalculation procedures rely on linear elastic layered theory for basic structural modeling. The results of these procedures are mainly based on the goodness of fit between computed and measured deflections. The goodness of fit has improved over the years due to increased computing power and better error minimization techniques. However, in many cases, improving the goodness of fit does not necessarily mean that the theoretical model better represents actual pavement response. If an existing pavement structure violates some of the fundamental assumptions of elastic theory, the goodness of fit should not be the determining factor of an acceptable solution. Other possible sources of variability include distress in the pavement layers, variations in layer thickness, nonlinear material response, and presence of bedrock or stiff layers (*8*).

Uzan (*9*) analyzed several existing backcalculation procedures and concluded that the main differences among them are related to the forward computation model used to predict the pavement response and the error minimization scheme. These forward computation models include numerical integration methods to solve a multilayer elastic system and approximation methods (*10*). Although the approximate methods are considerably faster, in some cases they may lead to unacceptable error in the forward computation of the pavement response that would be reflected in the computed moduli. For example, the method of equivalent thickness may produce erroneous results when the moduli do not vary in monotonously decreasing ways with depth (*10*). Common error minimization schemes include the minimization of the absolute or percent mean square error (MSE). The absolute MSE assigns similar weight to all deflections and it is affected more by the deflections close to the center of load application. On the other hand, the percent MSE (%MSE) gives greater weight to the outer deflections. The sensors farther from the load are divided by a smaller number (corresponding deflection) than the closer sensors.

Five backcalculation programs were evaluated in this research project: PEDMOD95 version 1.0, MODULUS version 5.0, ELMOD version 4.0, EVERCALC version 5.0 and MICHBACK version 1.0. The strengths and weaknesses of these programs were assessed and results were compared in terms of usability and accuracy. In addition, several technical characteristics of the packages were considered as summarized in Table 2. Based on the considerations listed in Table 2 and analysis of one of the sections (Section A) using the different packages, EVERCALC was selected as the baseline software for this study. It produced reasonably consistent results and provided the required flexibility.

The analysis conducted as part of the software evaluation also showed that when using the best possible fit between measured and computed deflections, the variability of the moduli computed for the different materials was very high. Considerations such as allowable ranges and seed values appeared to have more impact on the backcalculated moduli that the software package used.

TABLE 2 Main Advantages and Disadvantages of the Software Packages Evaluated

Software	Operation Principles	MS Wind.	Error Minim.	# of loads	Depth to Bedrock	Non-linearity	Comments
PEDMOD95 (WESDEF)	LEA (WESLEA)	Yes	%MSE	1	No	No	Only 3 iterations for optimization.
Modulus	Database LEA (BISAR)	No	MSE	Various	Yes (high variability)	No	Does not allow fixing subgrade modulus.
ELMOD4	Approx. (MET)	Yes	MSE or %MSE	Several loads/ sections	Yes	Yes	Some assumptions are violated by some of the test sections.
EVERCALC (v 5.0)	LEA (WESLEA)	Yes	%MSE	1	Yes	No	Sensitive to initial seed values.
MICHBACK	LEA (ChevronX)	No (1)	%MSE	1	Yes (or layer thickness)	No	Detailed optimization routine.

(1) At the time of the evaluation the Windows version was not available.

BACKCALCULATION PROCEDURE

A detailed backcalculation procedure was established to obtain more accurate and consistent backcalculated moduli. The average apparent surface moduli obtained using the deflections measured for the last five sensors (last column in Table 1) were adopted as seed values for the subgrade modulus. In cases where the structure could not be modeled with an appropriate error, the subgrade modulus value was allowed to float to account for moisture and compaction variations and stress-dependent behavior. The backcalculation was conducted for one layer at a time, processing from the bottom (subgrade) up. The moduli computed in the previous steps were used to control the range of possible values for all the underlying materials. A default value of 1,380 MPa was used when the backcalculated open graded drainage layer (OGDL) moduli were unreasonable; the OGDL thickness is 75 mm. Each backcalculation step was conducted several times with different seed values to avoid local minima in the error minimization. The set of moduli that resulted in the model with the lowest %MSE was selected in each case.

Subbase Moduli

The backcalculation results of the 21-B layer were relatively consistent except for some of the sections with a 75 mm subbase. However, this was expected because thin layers (75 mm or less) usually cause problems in backcalculation procedures. Given the similarity between the 21-B and the fill material (mostly 21-B with some large aggregate), the subbase and the subgrade were combined if the thickness of the 21-B was 75 mm or less. The moduli values determined were in reasonable agreement with those measured in the laboratory, particularly if the stress dependency of the material is considered (*11*).

Cement-Treated Base Moduli

FWD testing on the 21-A layer was done just days after the material was laid. Thus, the strengthening of the layer due to increased cement hydration had to be incorporated in the analysis. The increase in moduli was estimated based on unconfined compression tests conducted on 100 x 200-mm cylinders prepared in the field and cured in a moisture room (*5*). The modulus at each age was estimated using the relationships given in the AASHTO Guide for Design of Pavement Structures (*12*). Adjusting factors for the 21-A moduli were determined based on these estimates and the age of the layer at the time of testing (*11*).

HMA Base Moduli

The moduli of the 38 mm thick wearing surface layers could not be accurately determined using the software package. These problems were expected for the same reason discussed for the 21-B layer: backcalculation procedures do not typically work for layers less than 75-mm thick. Consequently, a combined HMA layer (combining BM-25.0 and wearing surface) was used. The moduli presented are for the combined BM-25.0/wearing surface layer.

A regression equation was fitted to the data to determine and adjust the modulus to a base temperature of 25°C. The average pavement temperature for each test was determined as an average of the values measured by thermocouples installed at the bottom of the wearing surface. The moduli backcalculated for all the seasonal monitoring tests (nine tests over the finished pavement) from January 2000 to December 2001 were used in the analysis. It appears that the model is similar to models presented by other researchers (*13*, *14*). The following is the resulting equation:

$$E_T = E_{25}\, e^{-0.031(T-25)} \tag{2}$$

where,
E_T = HMA Modulus (MPa) at temperature T;
E_{25} = HMA Modulus (MPa) at 25°C; E_0 = 7,125 MPa for this study; and
T = Temperature of the HMA layer during FWD measurement (°C).

The temperature correction model is shown in Figure 5. This temperature correction models are based on a wider range of temperatures than those presented elsewhere in (*11*). Several data points have been added at the low temperature range due to further testing at low temperature.

MODEL VERIFICATION

The best way of determining whether a given mathematical model is acceptable for pavement design is to compare the pavement response predicted by the model to that measured in actual field conditions. Although several attempts have been made to verify the different backcalculation procedures over the years, none has led to the conclusive verification of a specific mathematical model. No theoretical model constitutes the “truth;” they are all simplified models of reality (*7*). A verification of the layered linear elastic model used for backcalculation was attempted by conducting FWD tests directly on the embedded instruments.

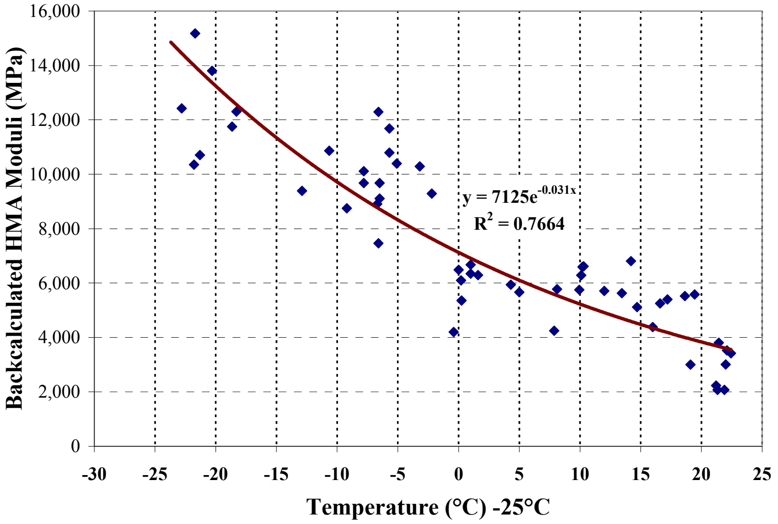

FIGURE 5 Backcalculated Resilient Moduli of BM-25.0 Layer Versus Temperature.

Pressure Cell Responses

FWD loads of approximately 31, 40, and 49 kN were applied on top of various pressure cells embedded in Section A. The temperature of the HMA layers was measured by thermocouples installed in the HMA. The response of pressure cells, embedded in the HMA base (AP2-1), CTA (AP5-3), and subgrade (AP7-2), were recorded by the data acquisition system. The first letter of the pressure cell identification categorizes the section in which the instrument is placed, the second letter identifies the instrument type (e.g., P for pressure cell), and the numbers identify the layer and the instrument number in that layer. The instrument responses are presented in Table 3.

TABLE 3 Measured and Computed Pressure Cells Response to FWD in Section A-40 KN loading (kPa)

Pressure Cell	**Depth (mm)**	Aug-00		Nov-00	
		T ~ 25°C		T ~ 10°C	
		Comp.	Meas.	Comp.	Meas.
Surface	0	568	568	568	568
AP 2-1	191	183	184	136	138
AP 5-3	419	27	26	23	15.2
AP 7-2	597	19	15	17	9

The average temperatures for the wearing surface during the August and December testing dates were 25°C and 10°C, respectively. The moduli of the HMA layers were determined for the testing temperature using the temperature correction model developed. Using KENLAYER, a linear elastic analysis model (*15*), the stresses at the instrument locations were calculated and compared with the measured responses (Figure 6). The computed stresses within the HMA closely match the measured responses, thus supporting the appropriateness of the backcalculated moduli (using EVERCALC). However, further testing is required for other environmental conditions.

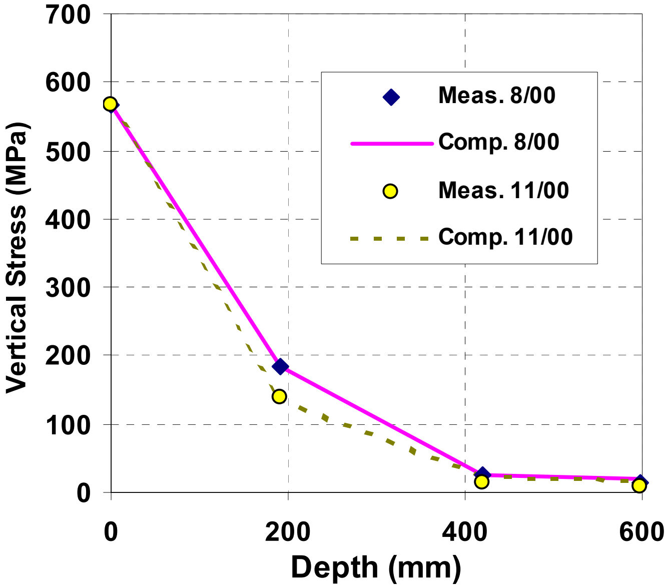

FIGURE 6 Measured and Compared Vertical Stresses in August and November 2000.

Since the granular subbase materials exhibited nonlinear behavior in laboratory tests, the pavement was also modeled to consider this layer as nonlinear. The following constitutive equation, relating the resilient modulus and the first stress invariant, was used to model the subbase:

$$M_r = k_1\theta^{k_2} \tag{3}$$

where,

θ = bulk stress or first stress invariant; and

k_1, and k_2, are regressions parameters.

The granular 21-B layer was divided into five sub-layers and the stresses at the mid-height of each sub-layer were obtained by the layered theory. The computed stresses at the subbase and subgrade levels computed using the nonlinear model were in better agreement with the measured pressure cell responses.

Strain Gage Responses

A similar procedure was followed for two strain gages in Section B. However, in this case, only high temperature measurements were used because the magnitude of the strain was too small at the low temperature to accurately detect it. Table 4 shows that the agreement between the measured and computed strains was good for the measurements take at the bottom of the HMA layer (instrument BSH 2-6L). However, the measured and computed strains were very different at the bottom of the open graded drainage layer (instrument BSH 4-1L), indicating either a problem with the strain gage or with the modulus computed for that layer. The complete theoretical profile of strains with depth according with the model used is presented in Figure 7.

TABLE 4 Measured and Computed Strains in Section B (microstrain)

Pressure Cell	Depth (mm)	T= 35°C, Mr = 5,200 Mpa				T=45°C, Mr = 3,900 MPa			
		Load = 31 kN		Load = 49 kN		Load = 31 kN		Load = 58 kN	
		Meas.	Comp.	Meas.	Comp.	Meas.	Comp.	Meas.	Comp.
BSH 2-6L	191	-31	-33	-45	-52	--	-36	--	-66.5
BSH 4-1L	267	--	-5	--	-8	-45	-5	-85	-10

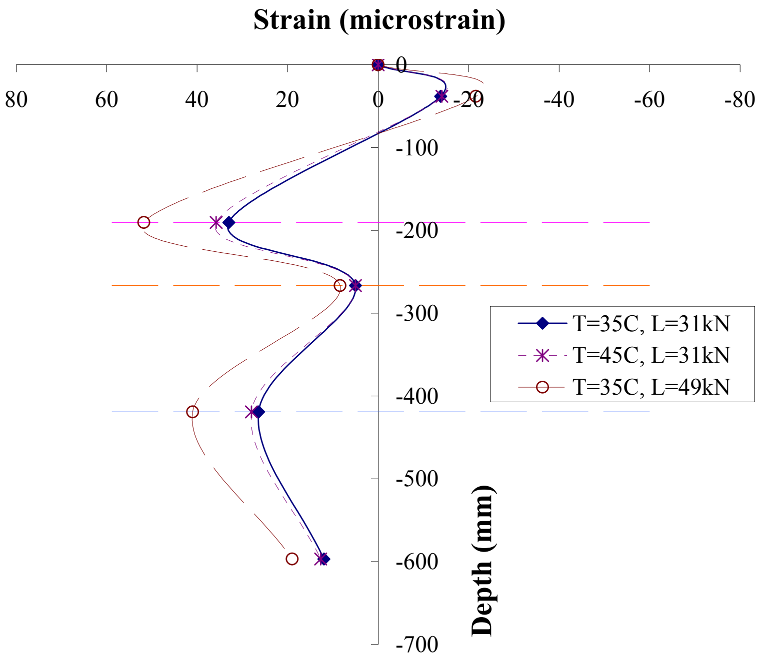

FIGURE 7 Distribution of Strain in Section B.

SUMMARY AND CONCLUSIONS

The paper compared *actual* pavement responses measured at the Virginia Smart Road with those determined using theoretical models and backcalculated layer moduli. FWD tests were conducted as each layer was built, and bimonthly after the pavement was complete. The moduli of each layer were backcalculated using several approaches. The response of the instruments to the FWD loading was recorded together with the moisture content of the granular layers and the temperature of the HMA layers. The moduli for the HMA layers were determined at different temperatures using deflections measured during different environmental conditions. An equation to adjust the modulus of the HMA base was developed using regression analysis.

The responses of the pressure cells were comparable to the stresses computed using a multilayer, elastic analysis utilizing the backcalculated moduli. The strains computed in the HMA layers were also consistent between measured and computed values.

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